Thermal conductivity measurements of warm dense matter by differential heating

Presented to JLF/NIF user meeting

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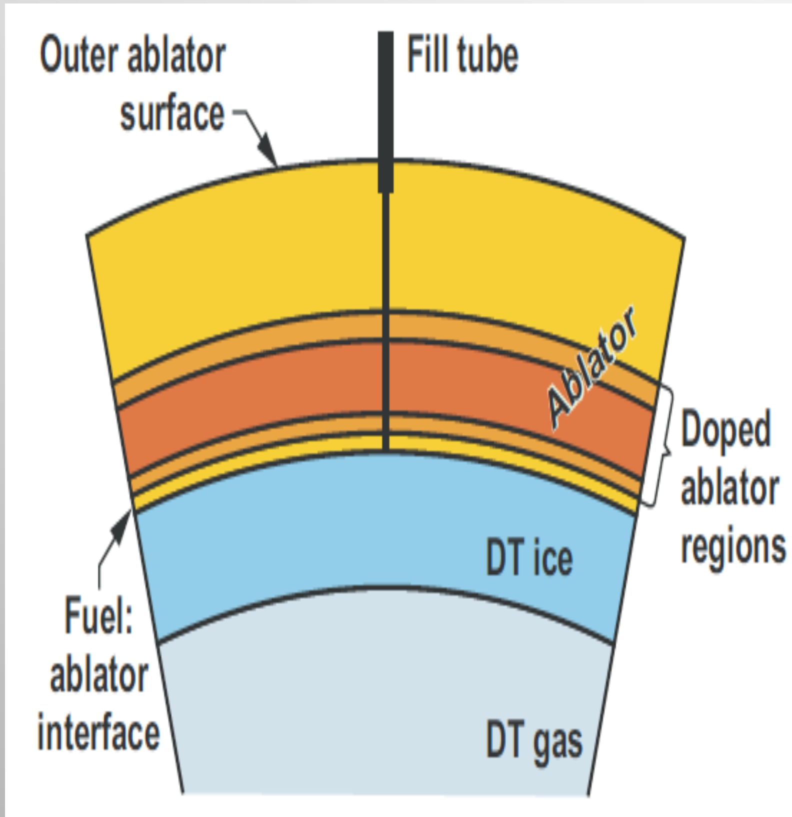
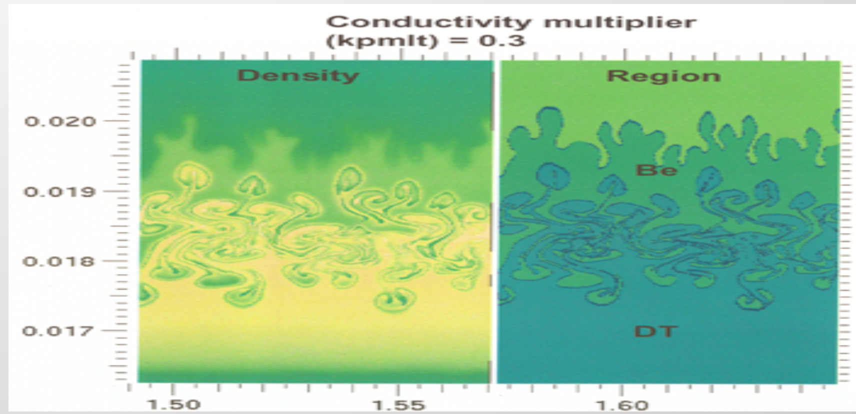
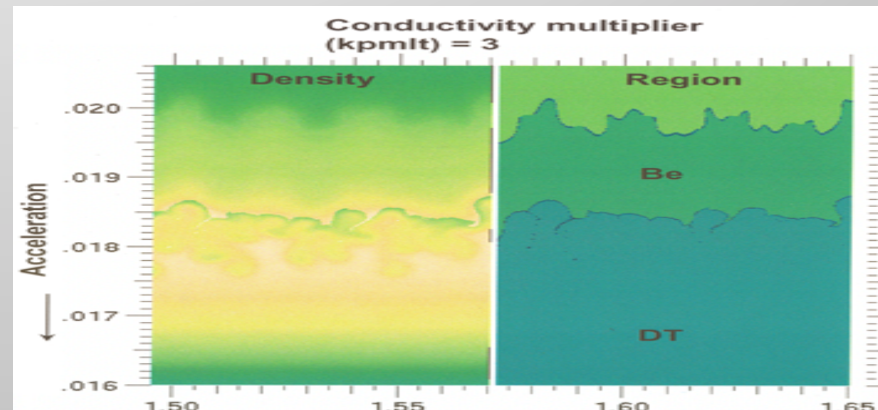
Outline

- Motivation to measure thermal conductivity
- Concept of differential heating
- Four platforms
  - Optical laser heating: ALS experiment (April 2014)
  - X-ray heating: OMEGA experiment (Dec. 2014)
  - XFEL heating: LCLS experiment (proposed)
  - Proton heating: Titan experiment (Nov. 2014)
- Summary

Motivation: thermal conductivity is a key factor in modeling hydro-instability growth in ICF targets

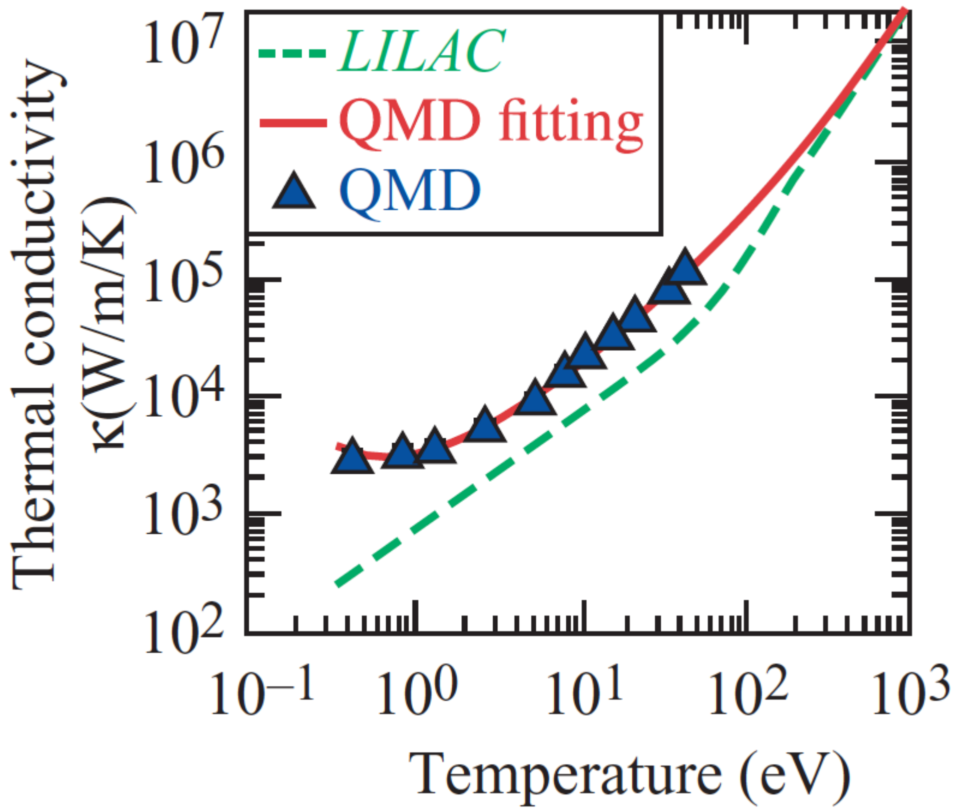


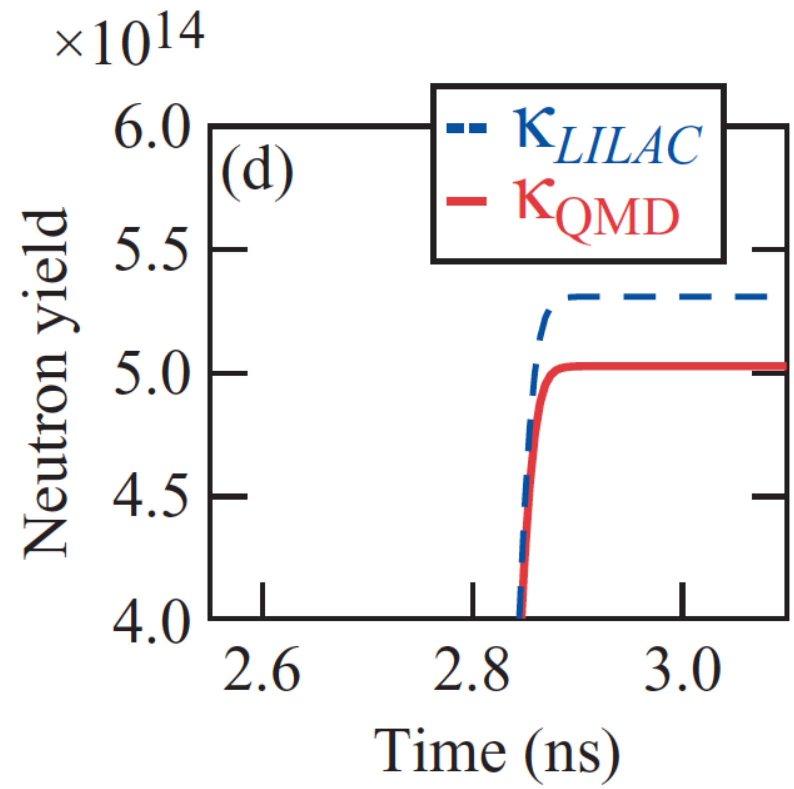




2D HYDRA simulations show the mix at fuel-ablator interface is sensitive to thermal conductivity (Hammel et al. HEDP 2010).

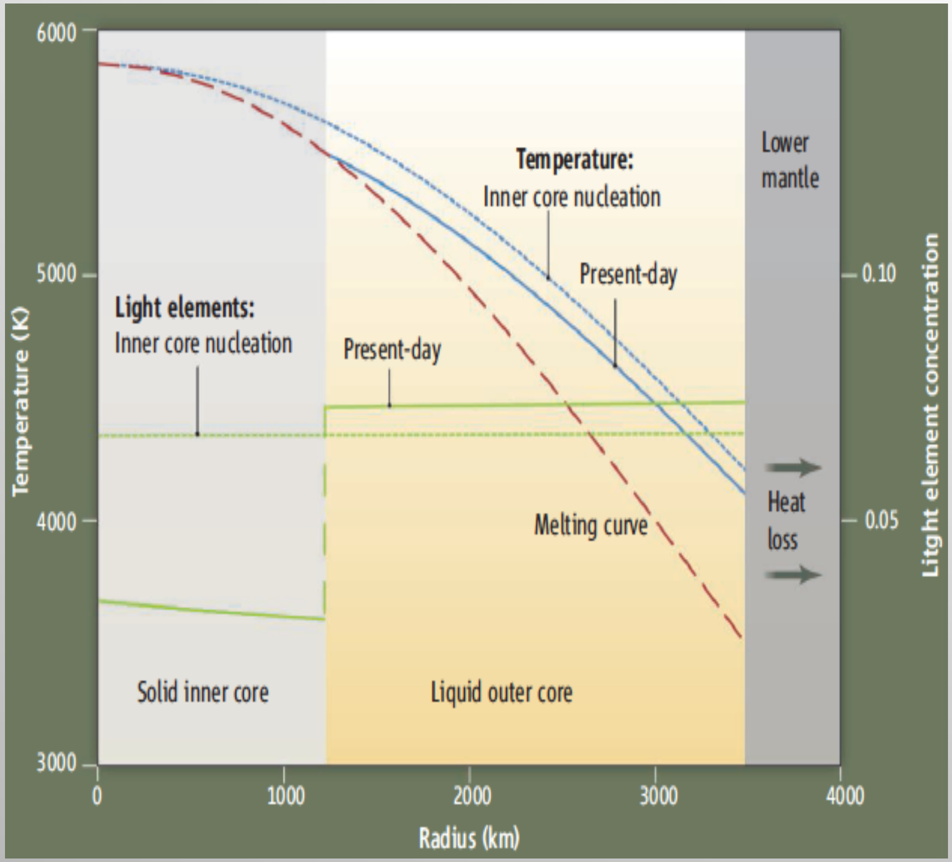
Motivation: thermal conductivity of the ICF fuel affects the total neutron yield





1D hydrosimulations using the new thermal conductivity have shown 20% variation in ICF target performance (Hu et al. PoP 2014).

Motivation: heat flux in Earth's core is part of power source for geomagnetic field



- Recent calculations of iron thermal conductivity at Earth's core conditions are 2-3x higher than current use (Pozzo et al. Nature, 2012).
- The conventional model of Earth core evolution, assuming thermal convection as the primary power for geodynamo, becomes questionable.

"High-pressure, high-temperature measurements are needed to pin down the actual conductivity of the core." --- P. Olson, Science 2013.

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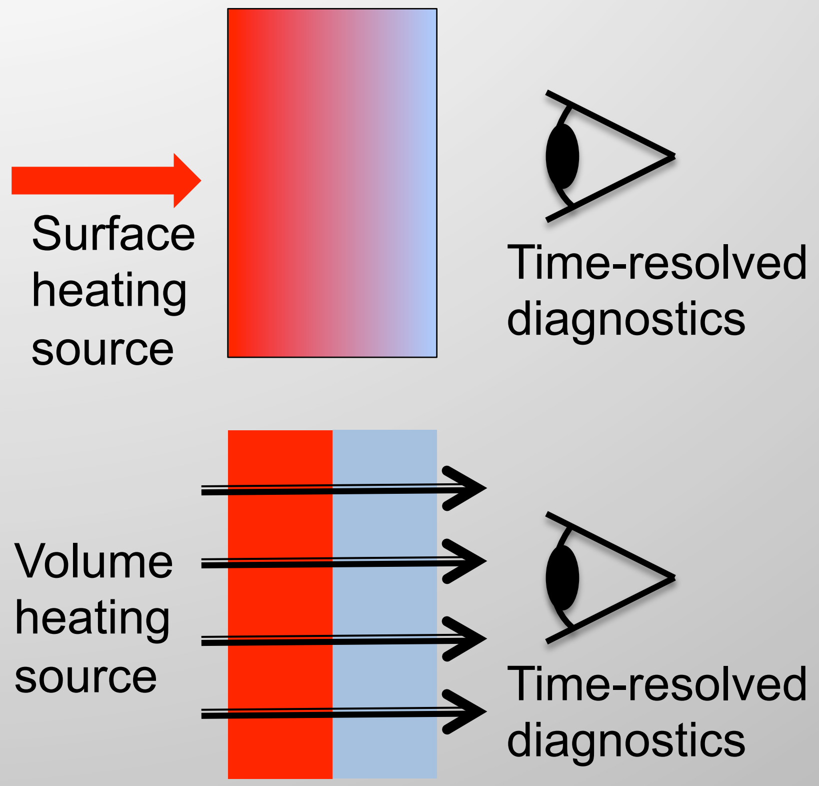
Concept of differential heating

- Definition of thermal conductivity: heat flow rate at presence of a temperature gradient.
- With surface heating sources, the temperature gradient is created inside one material.
- With volume heating sources, the temperature gradient can be created between two materials due to different absorption.
- The heat flow is then observed by time-resolved diagnostics.



We take advantage of temperature gradients to study thermal transport.

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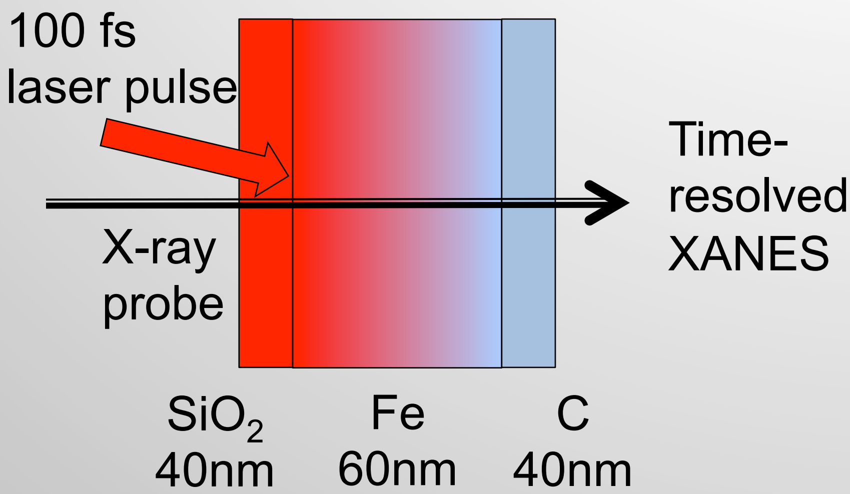
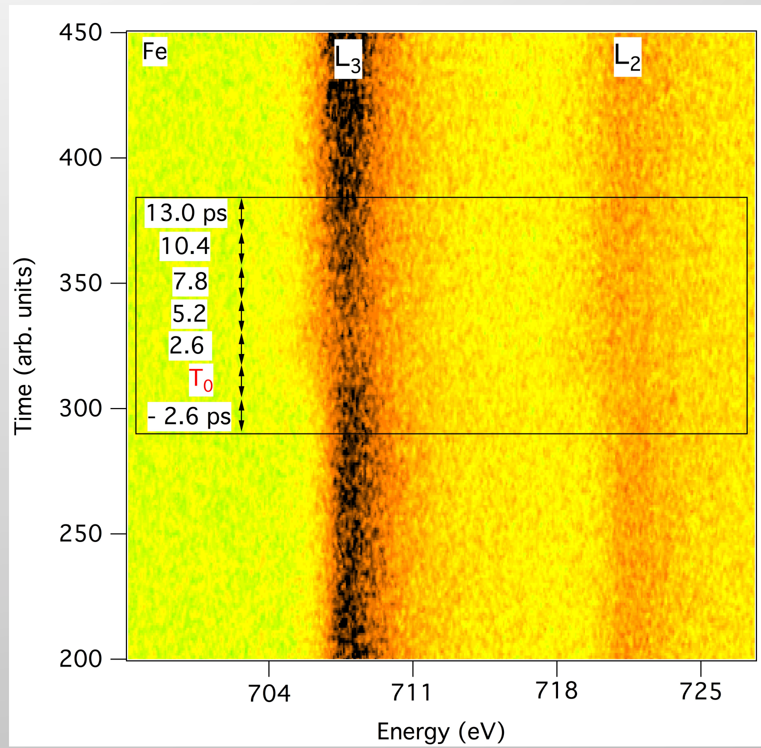
Optical laser heating experiment at ALS
(Advanced Light Source at LBNL)



Streaked XANES spectrum of iron L-edge

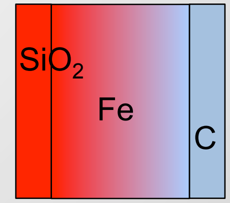


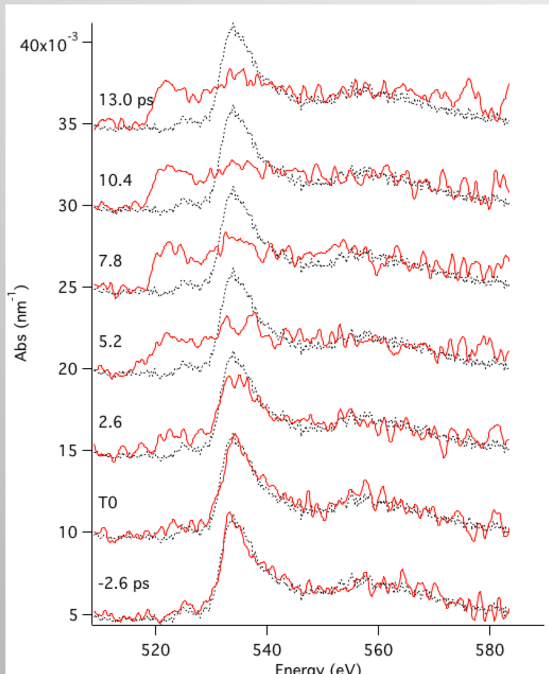
XANES Measurements:
(x-ray absorption near edge structure)

O K-edge,
Fe L-edge,
C K-edge,

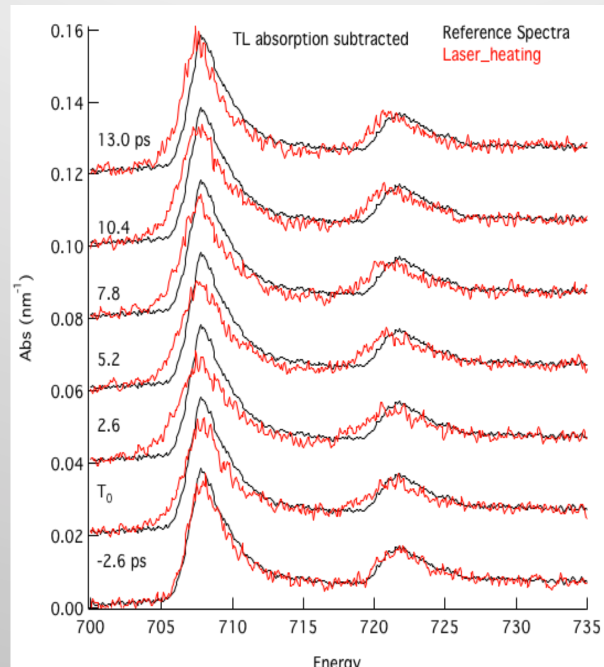
Smearing of the edge corresponds to temperature dependence of Fermi distribution (Cho, et al. PRL 2011), providing T vs time.

Streaked O, Fe and C XANES spectra show interesting time evolution

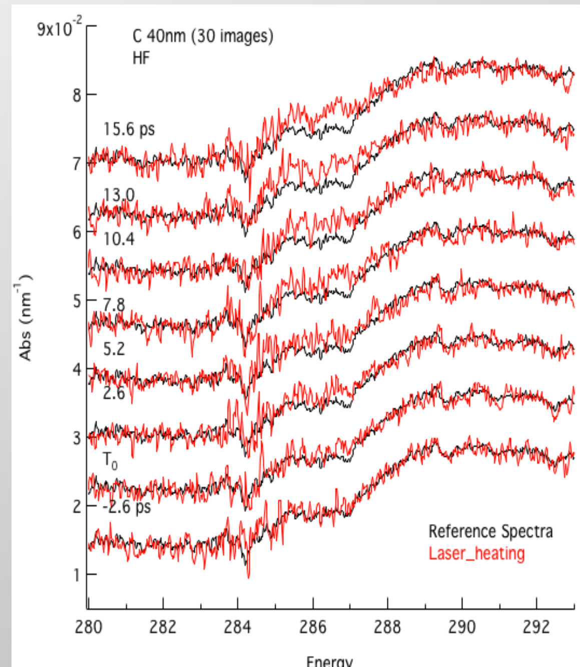




Constrain ballistic distance



Sensitive to electron-ion coupling



Constrain Fe thermal conductivity

Poster by Amalia Fernandez Panella, et al.

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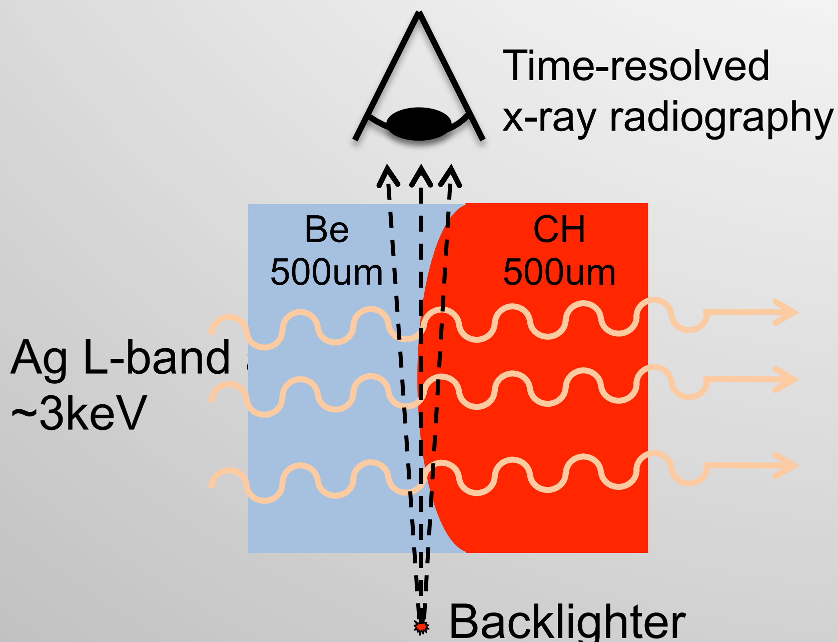
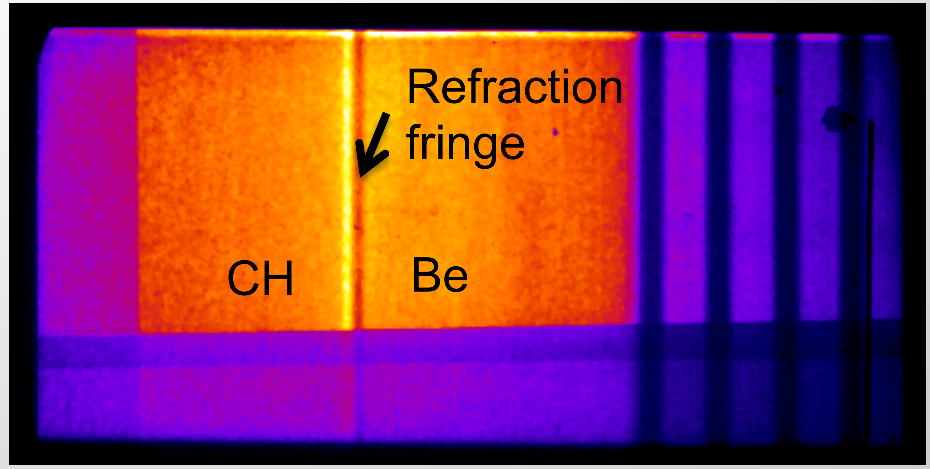
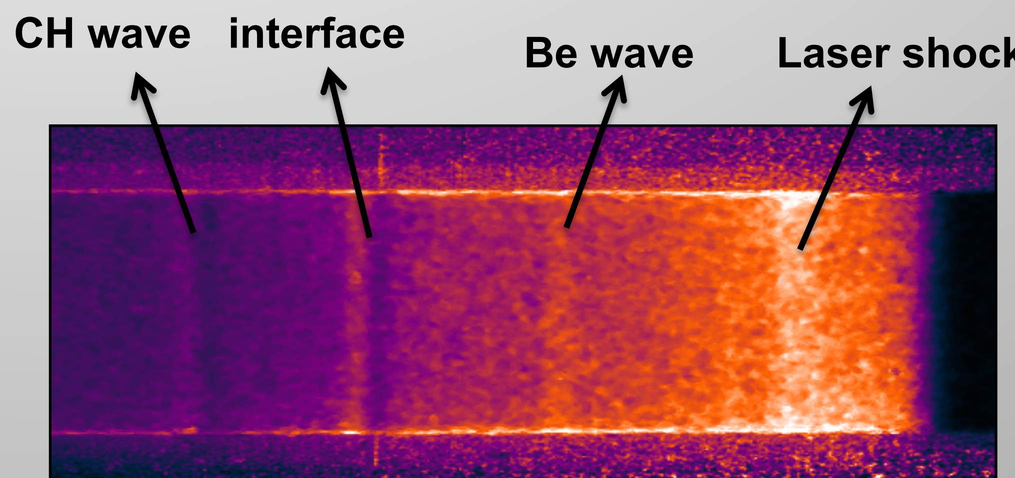
OMEGA experiment on CH/Be







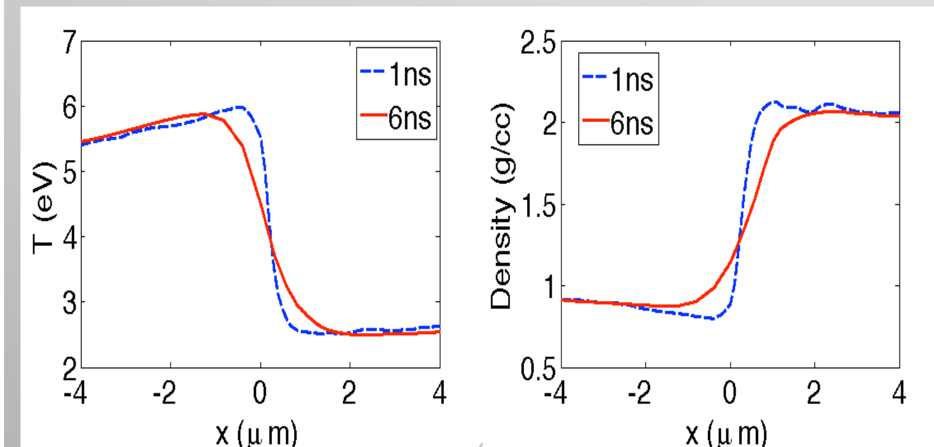
- Heating by laser-generated x-rays
- The interface is probed by x-ray radiography

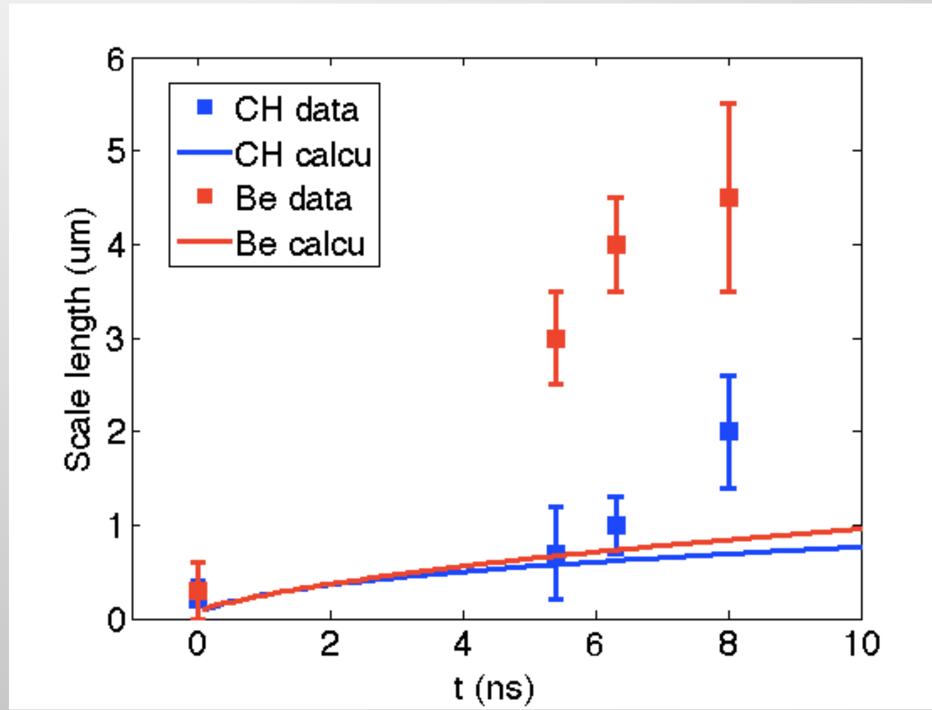
The radiograph contrast is enhanced by refractive effect (Ping, et al. JINST 2011)

Data analysis indicates higher thermal conductivity than model prediction

$$\begin{cases} \rho_{CH} C_{CH} \dfrac{\partial T_{CH}}{\partial t} = \dfrac{\partial}{\partial x}\left(\kappa_{CH} \dfrac{\partial T_{CH}}{\partial x} \right) \\ \rho_{Be} C_{Be} \dfrac{\partial T_{Be}}{\partial t} = \dfrac{\partial}{\partial x}\left(\kappa_{Be} \dfrac{\partial T_{Be}}{\partial x} \right) \end{cases}$$

Scale length vs time





More data from OMEGA shot in Dec. 2014 at higher temperature by 2-side heating. Analysis is under way.

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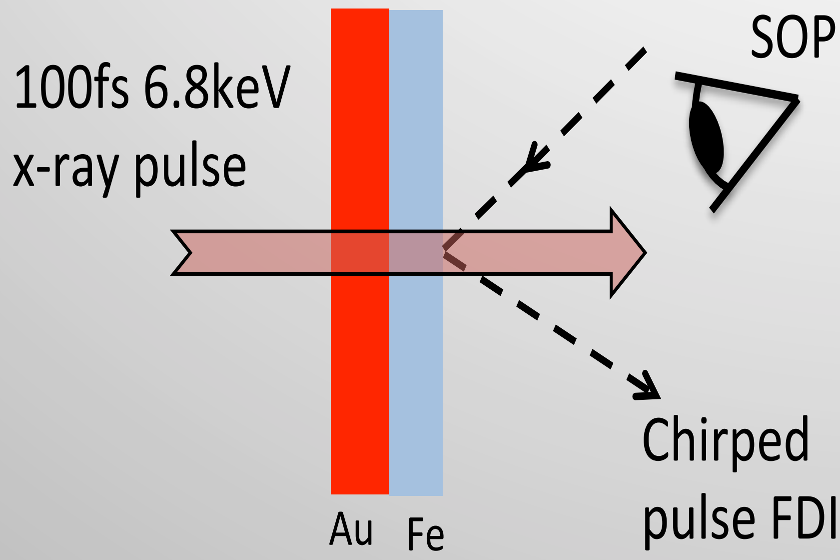
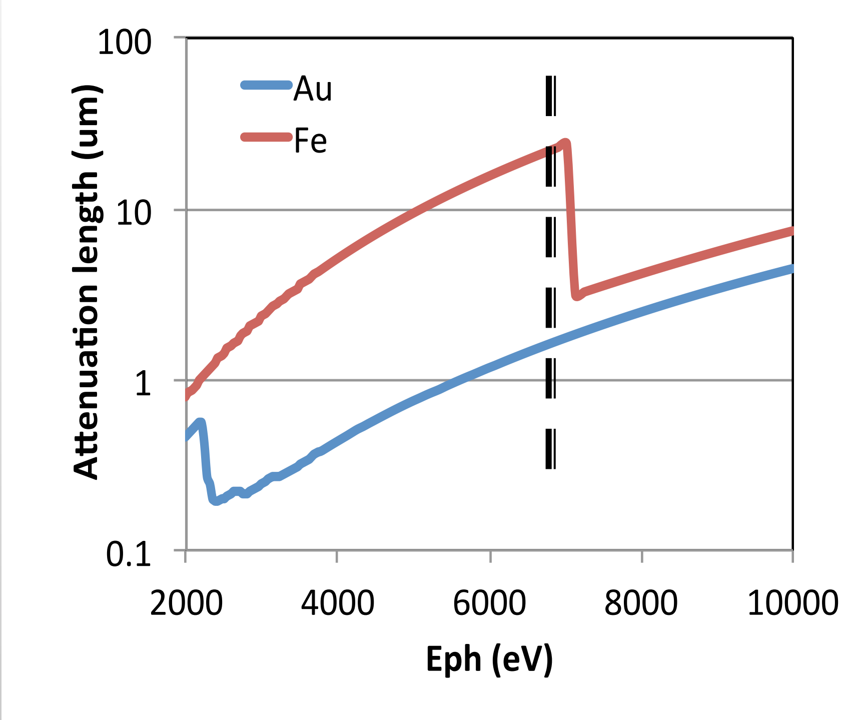
LCLS experiment on Au/Fe



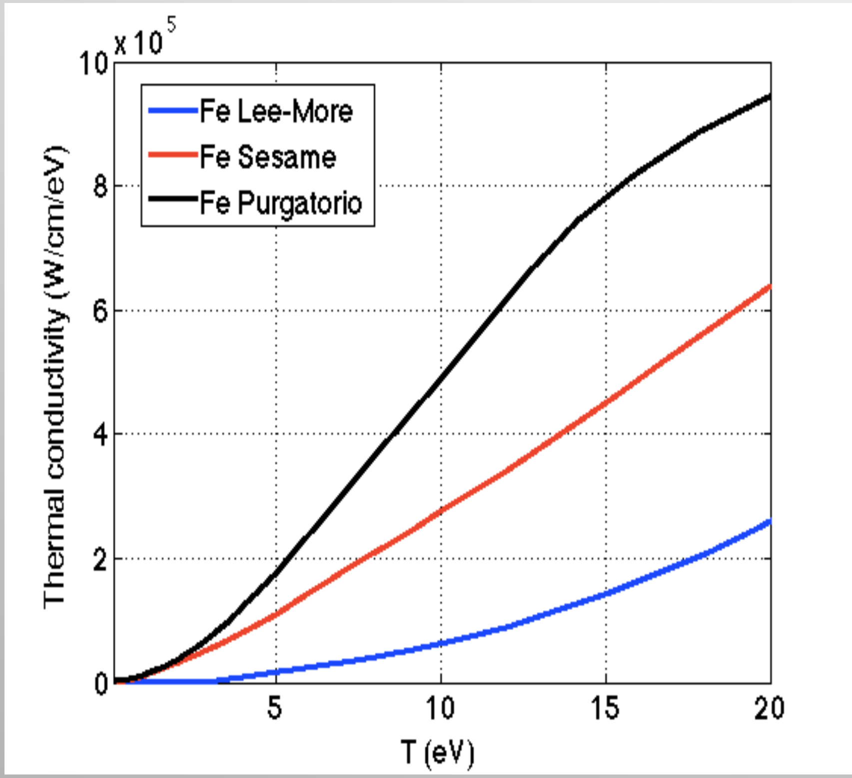
X-ray attenuation length in Au and Fe



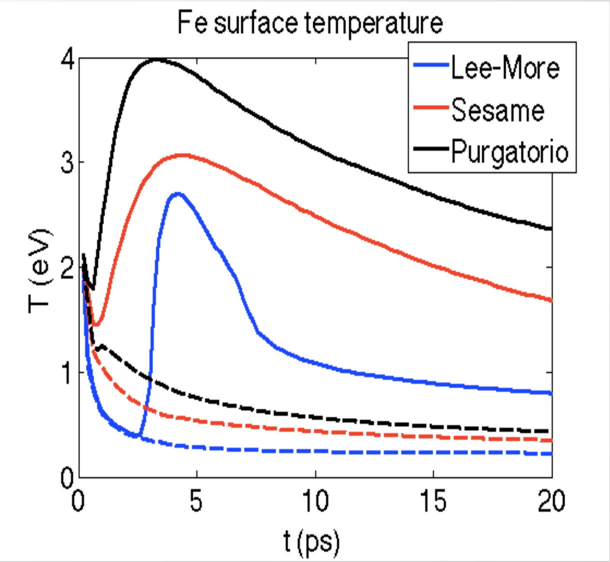
- Fe is 30-50nm to ensure thermal conduction is dominant over expansion cooling.
- Streaked optical pyrometry (SOP) measures Fe surface temperature vs time.
- FDI measures surface expansion and reflectivity/emissivity.

Calculations have confirmed measurable difference between three models

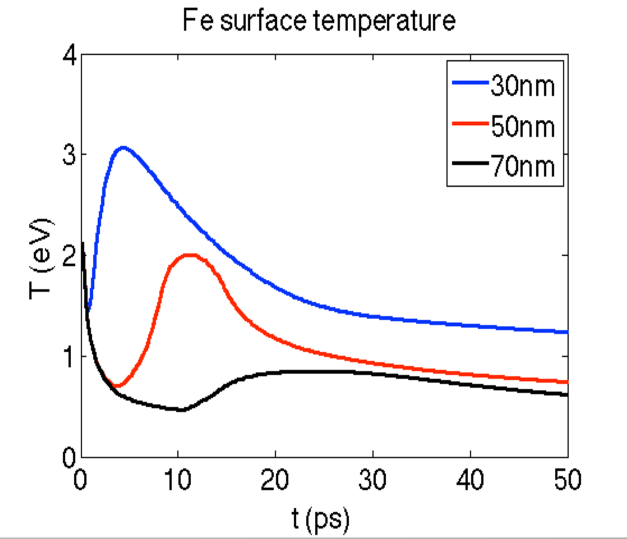
Predicted Fe thermal conductivity by three models



Predicted Fe surface T by three models



Vary Fe thickness



Proposal submitted for LCLS beam time.

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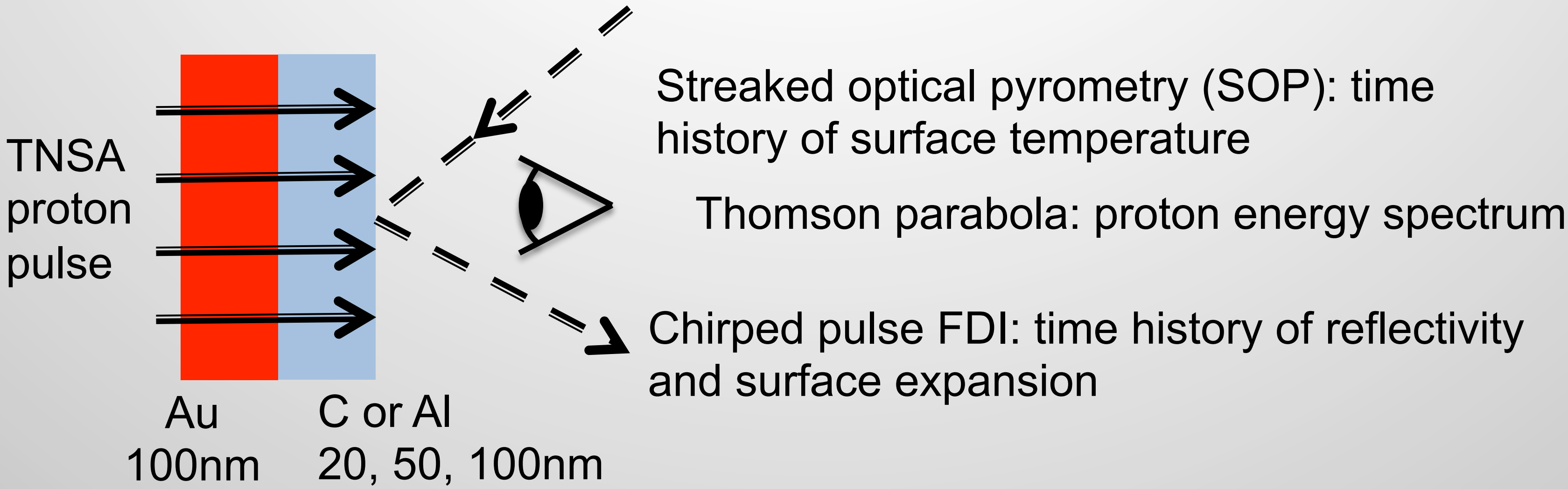
Titan experiment on Au/Al, C

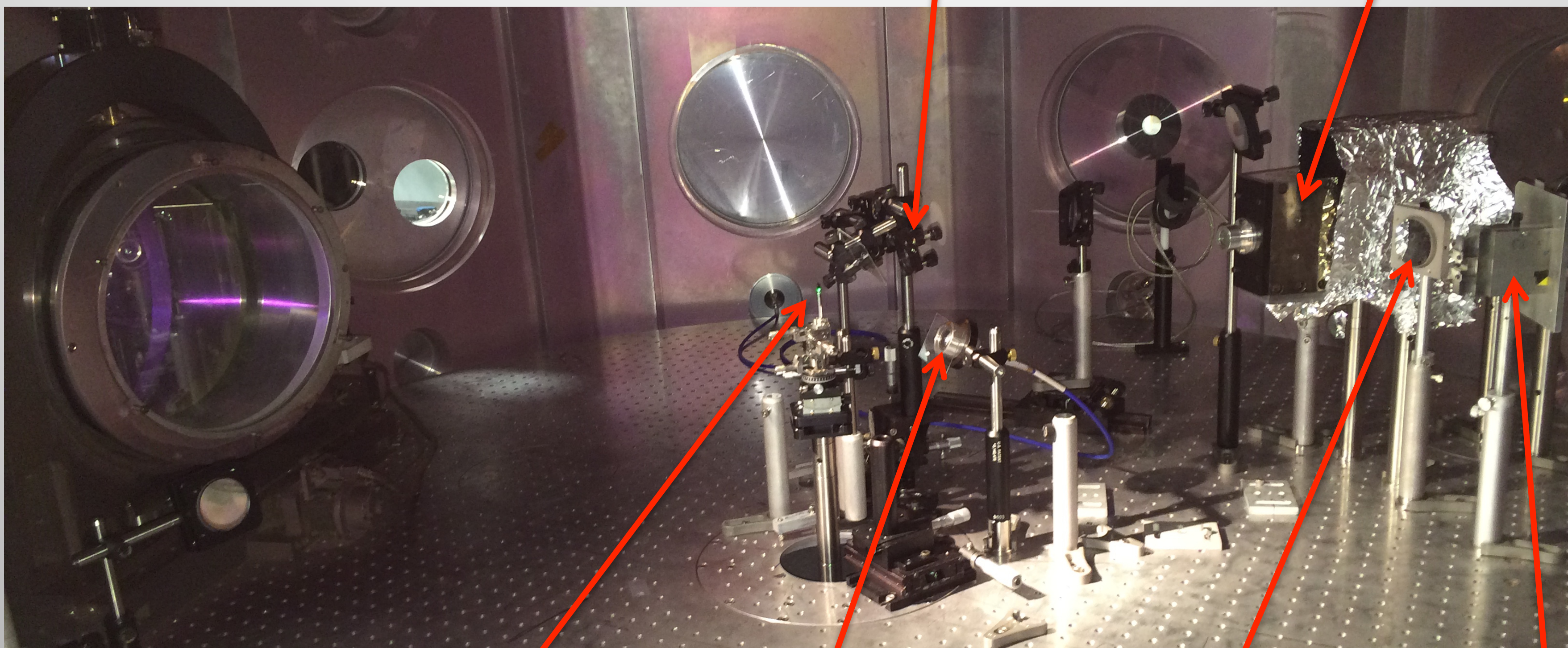


Experimental objectives:

- Proton differential heating of double-layer targets
- Thermal conductivity from temperature time history of the low-Z layer surface
- Electrical conductivity from reflectivity
- Test Wiedemann-Franz law in warm dense matter: $\kappa / \sigma = L\ T$

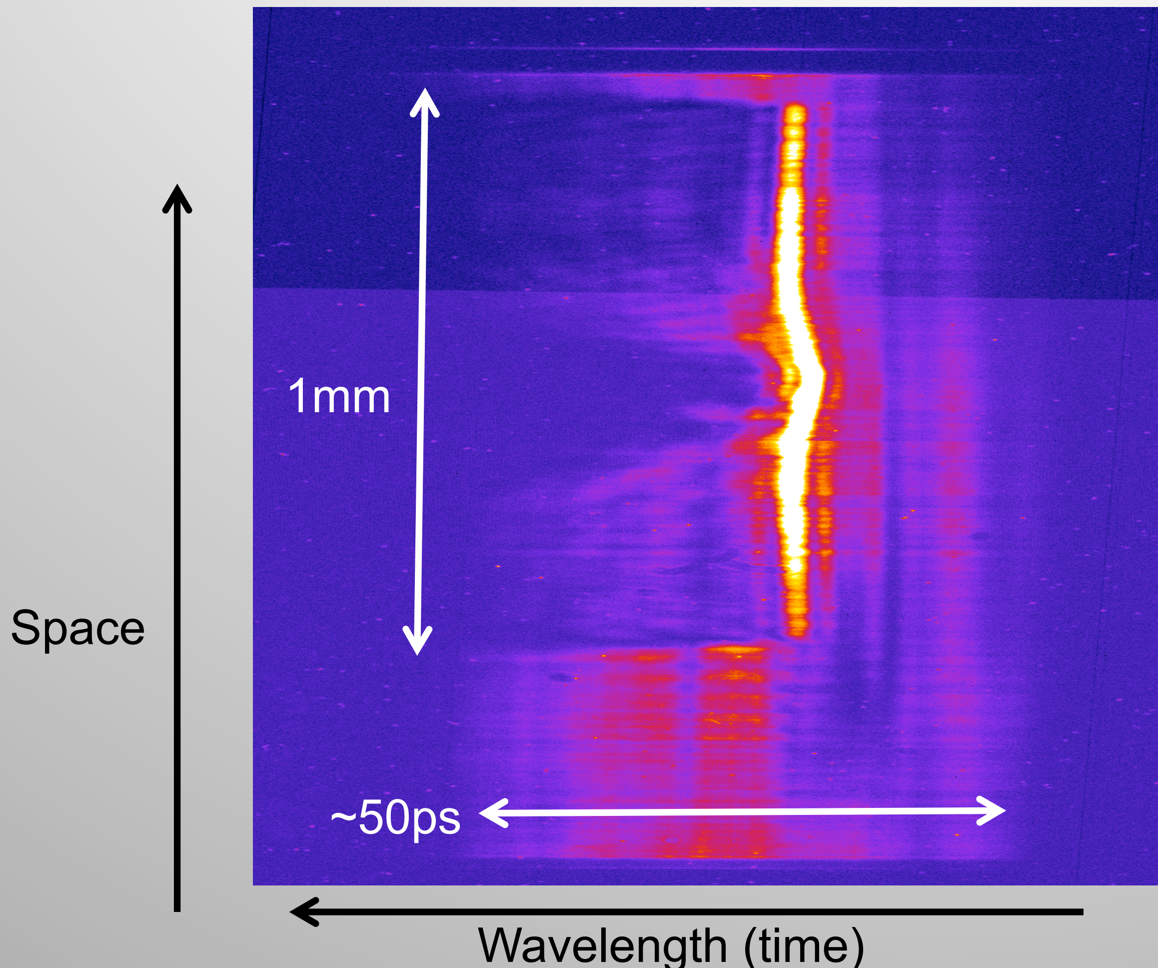
Poster by Andrew Mckelvey, et al.

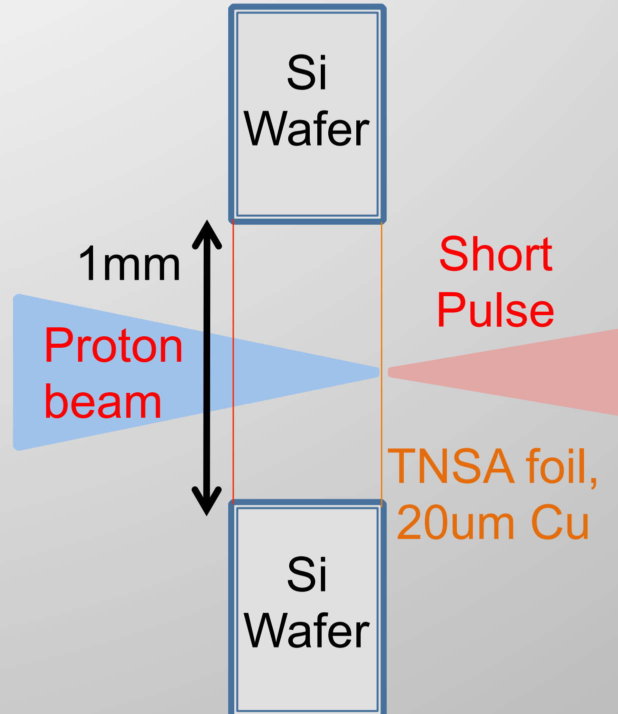
Titan Setup


SOP lens
Thomson Parabola for proton/ion energy spectra
Target at TCC
Fiber lens
Mirror for FDI
Electron spec.

At 150J, heated area is much larger than expected

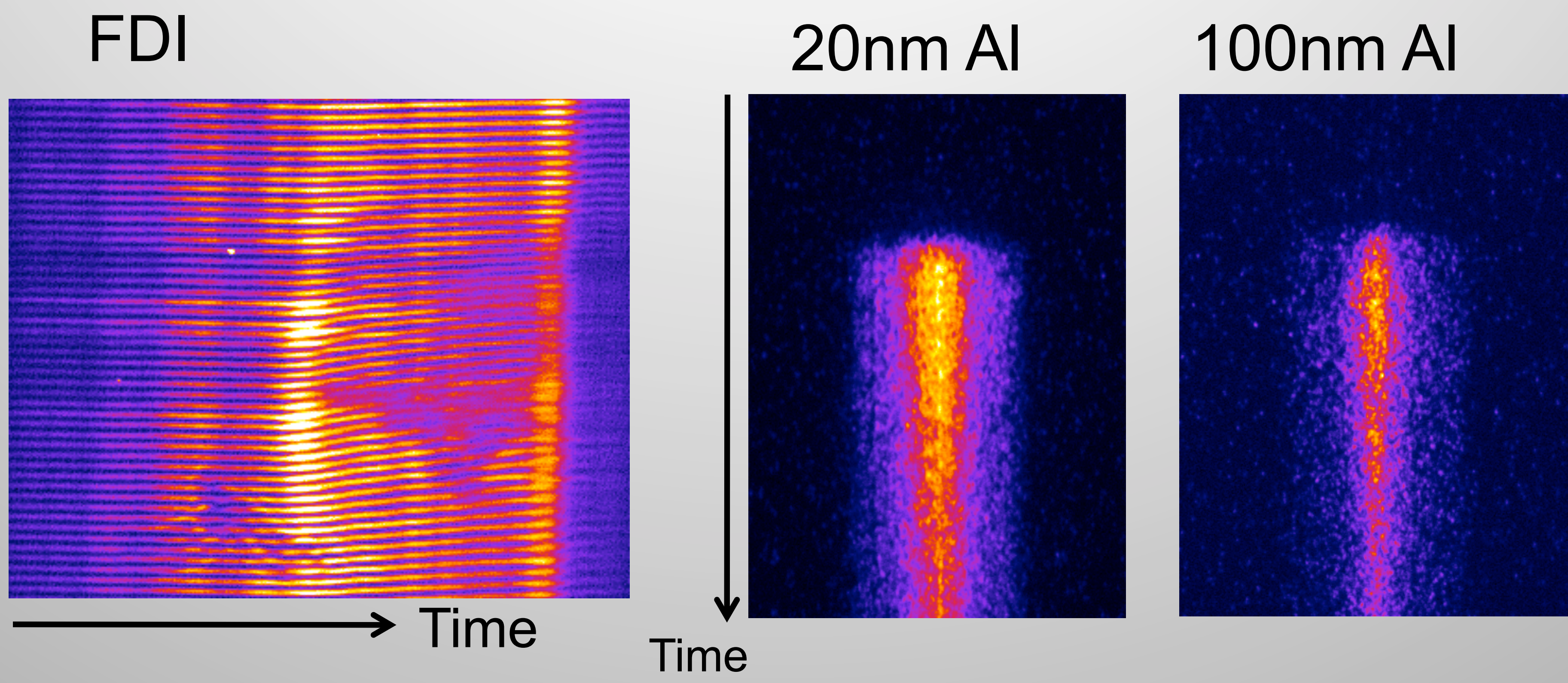
FDI image, reflectivity only





We found Al becomes hotter than Au, likely due to electron heating or charge effect.

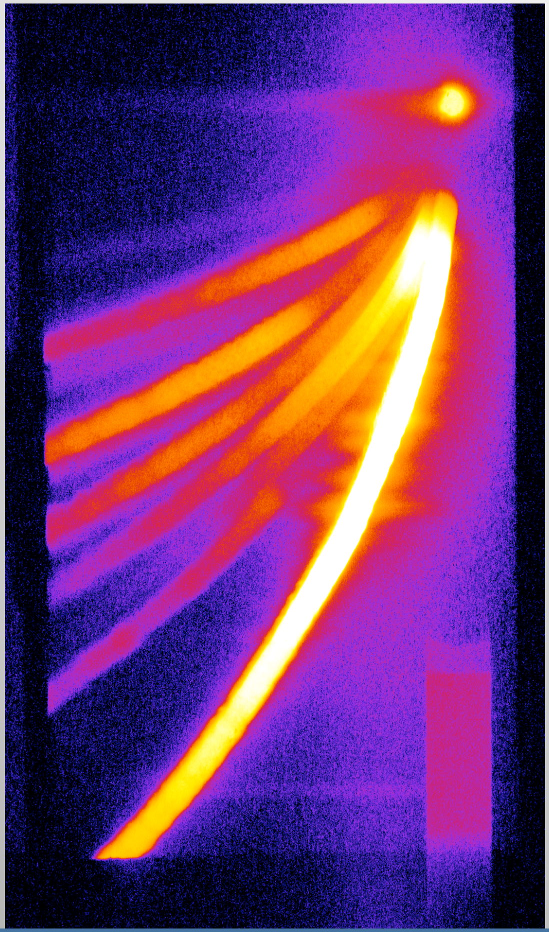
Good data at 15-30J



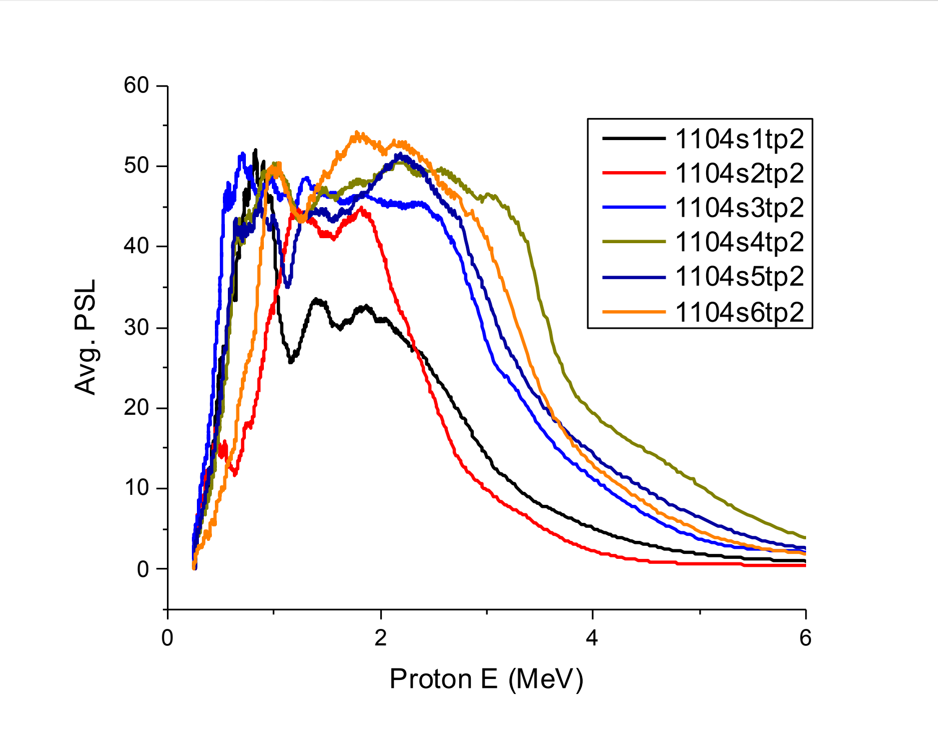
At lower laser intensities, data show the expected trend: Au is hotter, thicker target is cooler.

Proton energy spectrum is recorded every shot

TP image in log scale

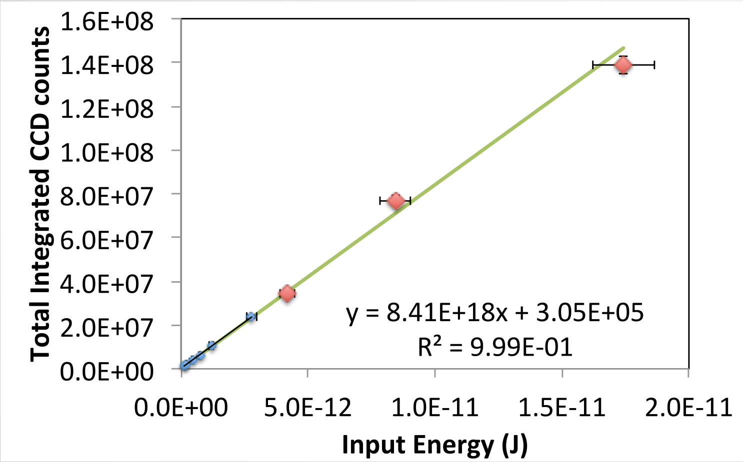


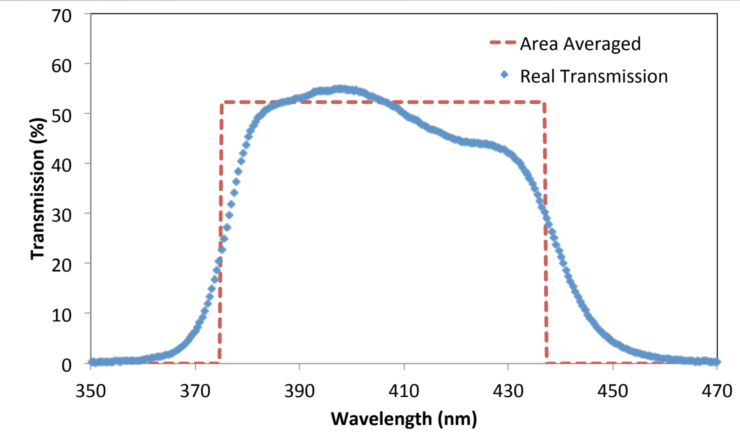
Energy spectra



Poster by Joohwan Kim, et al.

Absolute calibration of streak camera and SOP optics is needed to obtain temperature



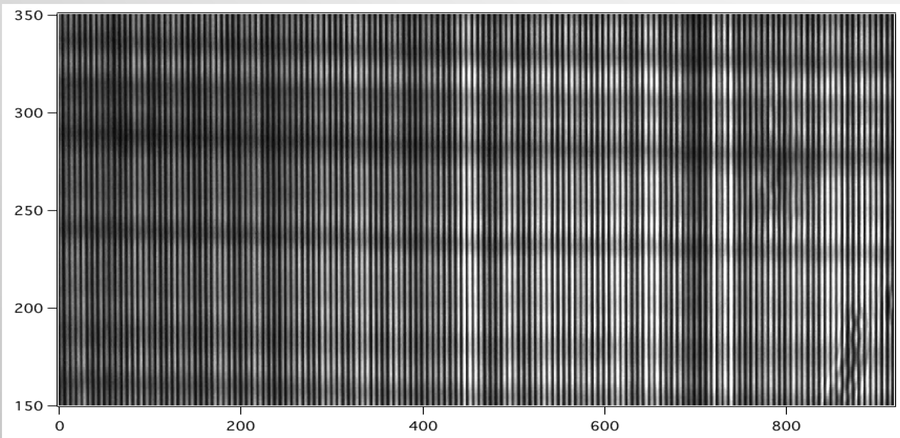


- Time resolution of C7700 Hamamatsu streak camera was measured to be 6ps.
- The streak camera was absolutely calibrated at 400 nm using Europa laser.
- Optics transmission (lenses, mirrors, window) was calibrated in-situ using 400nm CW laser
- All ND filters were calibrated
- Linearity at various SC gain was measured.
- Spectral transmission of the 400nm bandpass filter was calibrated.
- ……

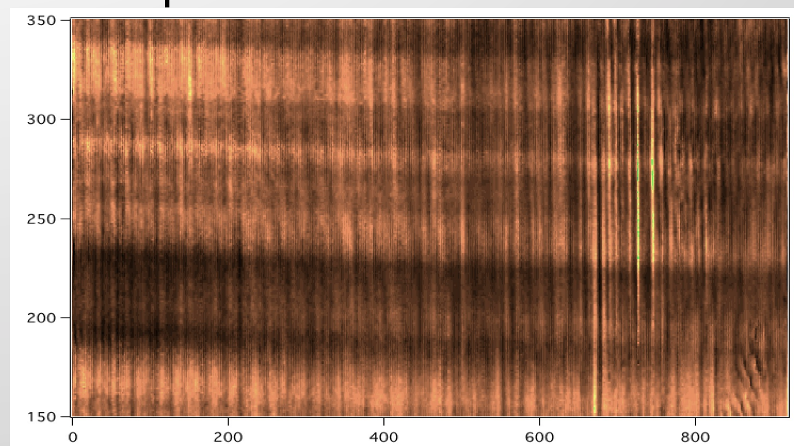
Calibration work was performed before and after Titan time on Europa laser.

FDI data provide time history of both reflectivity and surface expansion

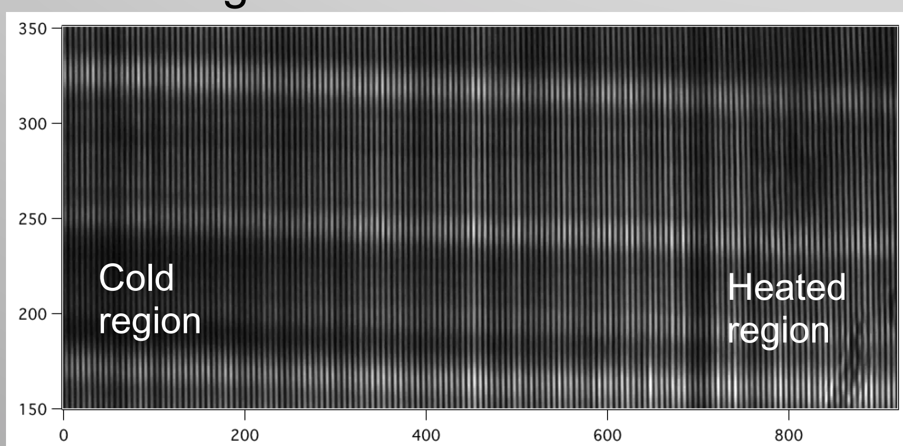
Before shot



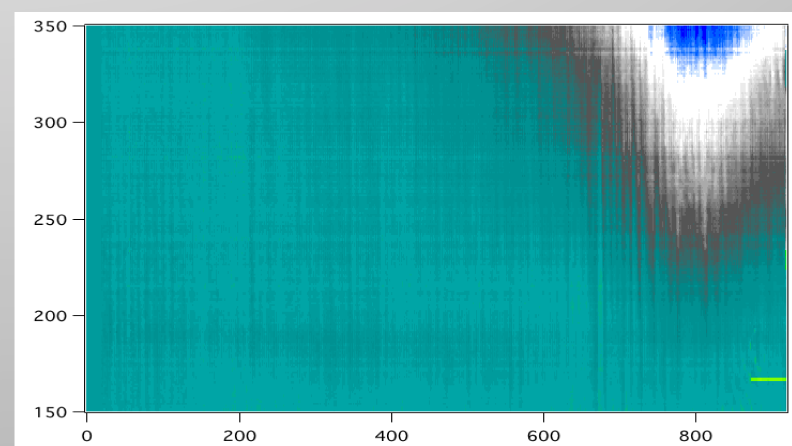
Amplitude distribution



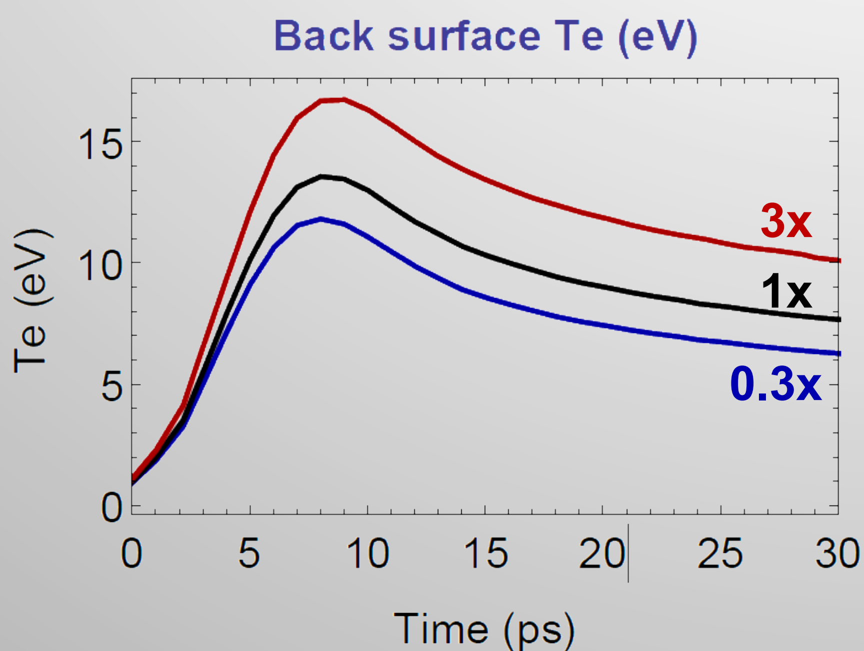
During shot

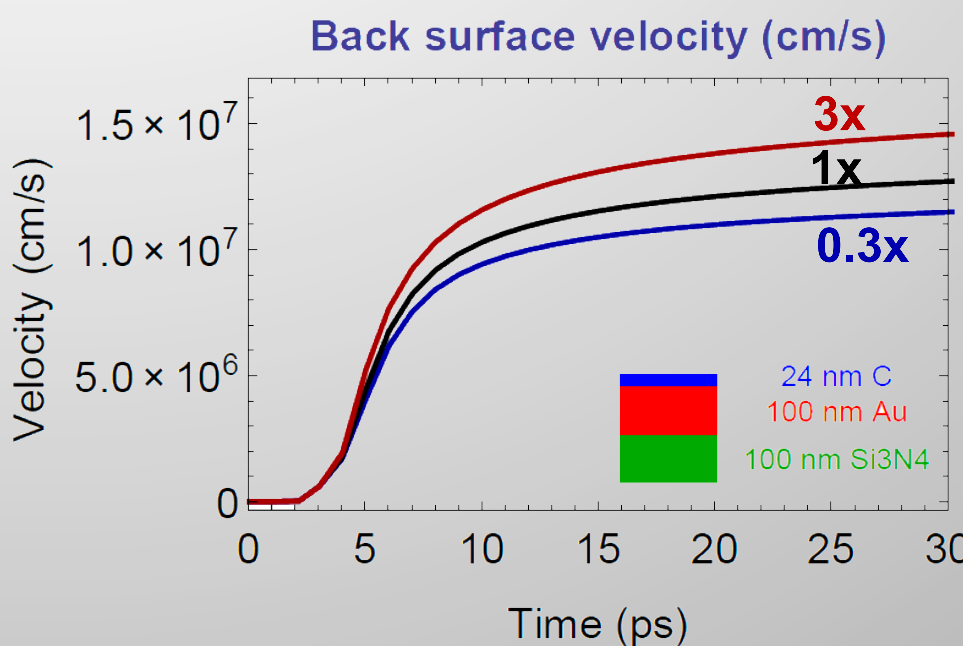


Phase distribution



Hydrodynamic simulations show sensitivity to thermal conductivity



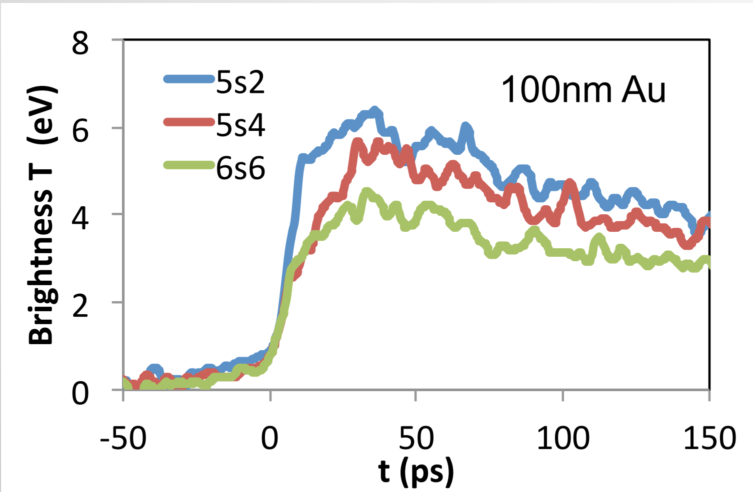


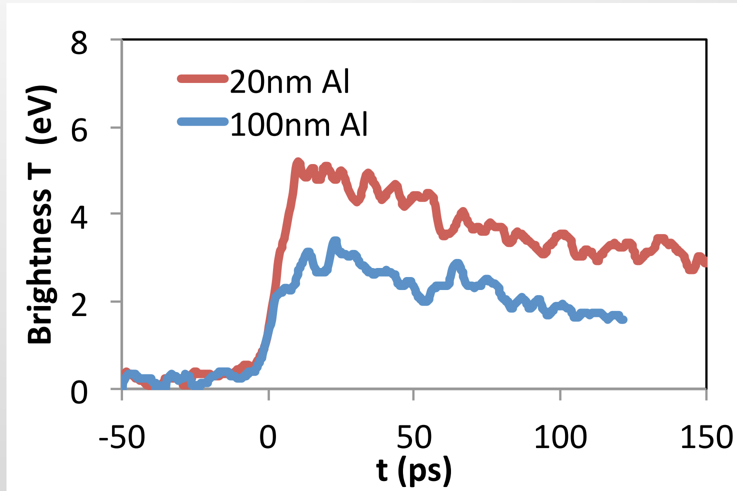
Measured proton spectra are used as simulation input

3x change in thermal conductivity results in peak temperature change 2-3eV.

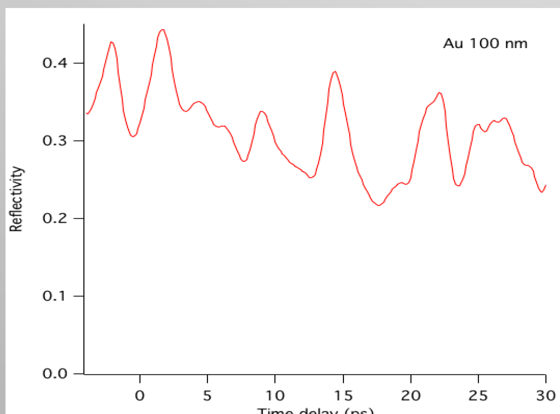
SOP data with emissivity from FDI confirm Au is hotter than Al

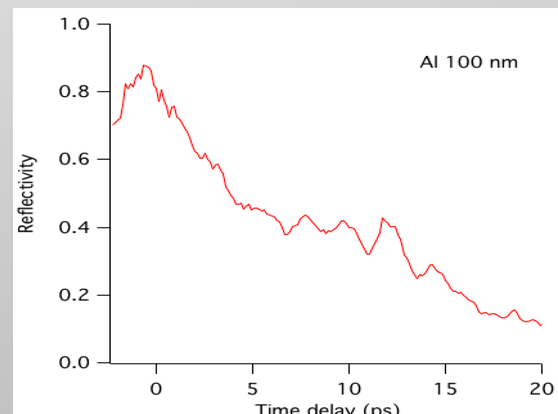
$$Intensity \propto (1-R)\frac{1}{e^{h\nu/T}-1}$$





Brightness T vs time





Reflectivity vs time

Further data grouping with proton spectra is under way.

Summary

- Differential heating is a versatile method for thermal conductivity measurements.
- Four platforms
  - ALS experiment (April 2014): optical laser heating+ XANES probe
  - OMEGA experiment (Dec. 2014): x-ray heating+ x-ray radiography
  - LCLS experiment (proposal submitted): XFEL heating+ optical probe
  - Titan experiment (Oct-Nov. 2014): proton heating + optical probe
- Titan experiment is successful
  - High quality data of SOP, FDI and proton spectra
  - Calibration and analysis of raw images have been completed
  - Data show the expect trend for thermal conduction

Three posters by Amalia Panella, Andrew Mckelvey and Joohwan Kim.

This project is supported by DOE OFES Early Career program.

JLF laser operation is excellent during the Titan campaign

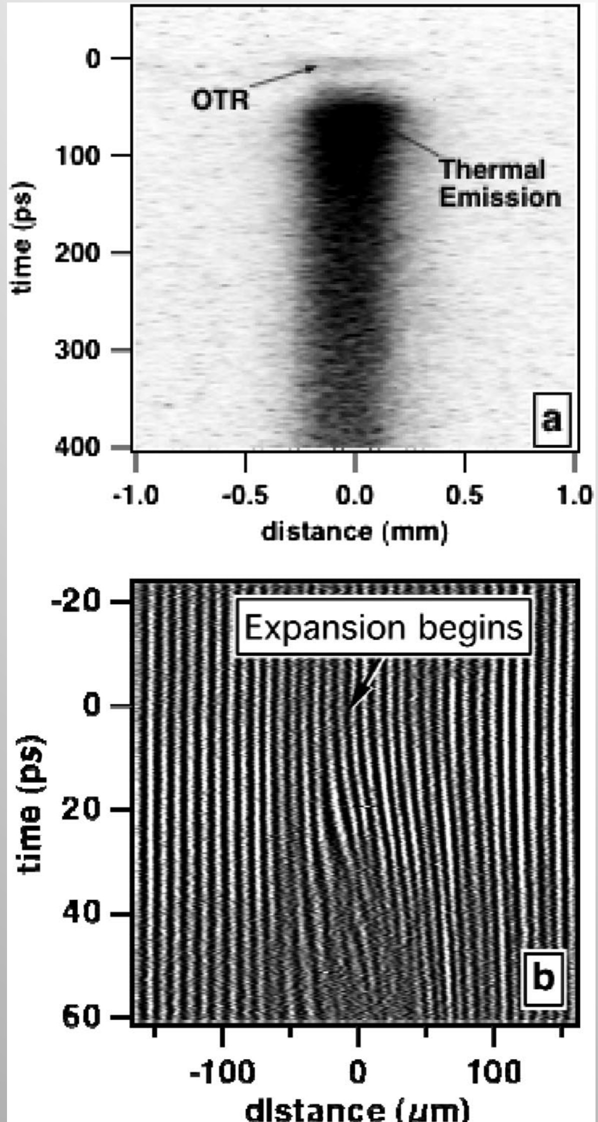
- Total 68 shots, multiple data sets
- Highest energy at shortest pulse: 182J
- Most shots a day: 7 shots at Titan plus 6 two-beam shots at Janus, thanks to lunch time shift
- 3-wk Europa time for absolute calibration
- Target fab support: making targets *in situ*

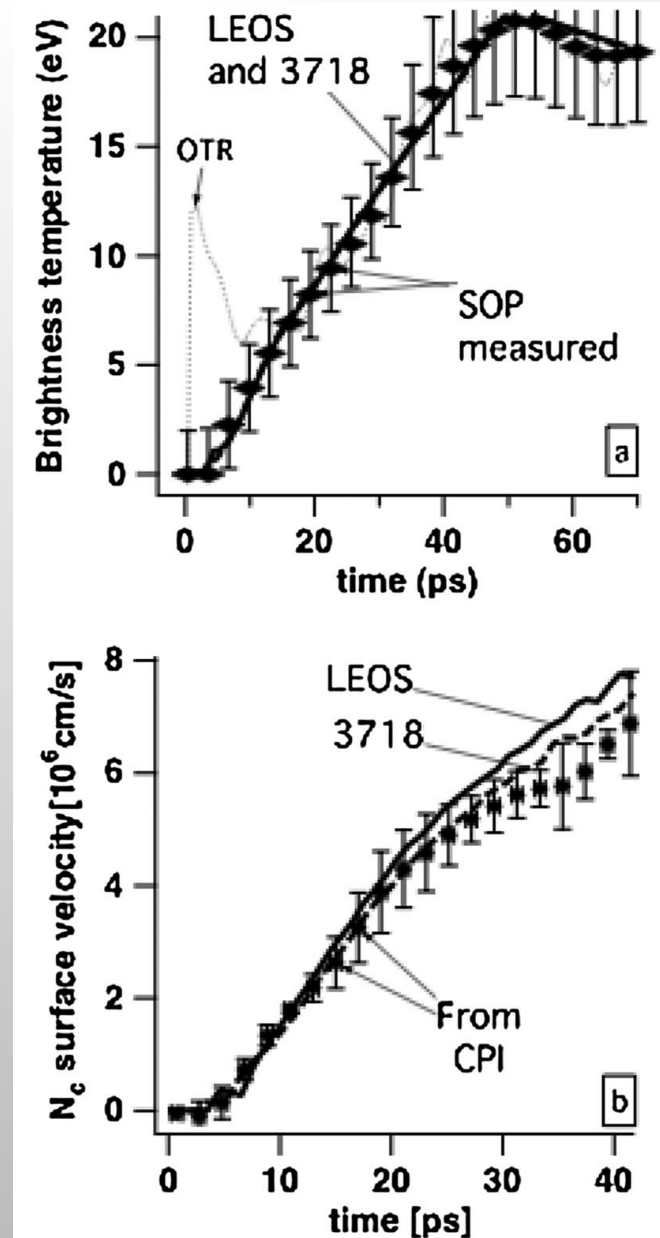
Thanks JLF staff for this efficient run!

- More staff is needed to support experiments and maintain facility.
- Higher shot rate and more shot days

Backup slides

Previous work





Dyer, et al.
PRL 2008